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A STUDY OF FUNDAMENTAL FACTORS PERTINENT TO MICROBIOLOGICAL WASTE CONVERSION IN CONTROL OF ISOLATED ENVIRONMENTS

C. G. Golueke

W. J. Oswald

H. K. Gee

SANITARY ENGINEERING RESEARCH LABORATORY
COLLEGE OF ENGINEERING AND SCHOOL OF PUBLIC HEALTH
UNIVERSITY OF CALIFORNIA
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Scientific Report No. 2

Eighth Quarterly Report

31 March 1965

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OFFICE OF AEROSPACE RESEARCH
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ABSTRACT

The report describes experiments with an algatron system (i.e., one that involves the use of a mechanically rotated culture) and presents a design of a system to support two men. An average algae yield of 1500 mg/l/day was obtained at inner and outer light intensities of 225 and 270 ft-c, respectively, the maximum light intensities obtainable with the available light source. From 87 to 91 per cent of incoming volatile solids were stabilized at detention periods from 0.25 to 1 day. No relation was noted between detention period and removal of P, Mg, Ca, and N. Low temperature distilled water yield was 1.83 ml/sq m/min (ambient relative humidity, 80 per cent). Water losses from an algal culture and from a carbon black suspension were closely similar, about 5 per cent greater than the loss from water alone. Design estimates based on the experimental conditions indicate that a maximum of 11 Algatrons, each 18 in. in diameter and 4 ft long would be required per man for gas exchange, waste treatment, and water recovery (about 300 liters/day).

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1. INTRODUCTION

1.1 Scope of the Investigation

Within the scope of the investigation were those studies required for attaining the objectives of the contracted work, namely: 1) determining the combination of environmental factors which would bring about the most efficient functioning of the algatron and the microterella systems with respect to gas exchange, waste disposal and treatment, and water exchange; and 2) making a preliminary design of a unit in which two 70-kg men could be made a part of a closed environmental system.

The subject matter of the investigation was in keeping with the fact that the ultimate objective of the contracted research is the development of design criteria for microbiological environmental control systems capable of supporting human life in isolated environments for indefinitely long periods of time. It has been shown conclusively by the authors that microbiological waste conversion is an essential to these objectives. To obtain design criteria for sustained systems, experiments with more limited objectives have been conducted on complex integrated biological and physiochemical models. Model systems which have been studied are the "Daisy Mae Converter" (solid waste treatment based on phase separation by differential settling), the microterella, and the algatron. With the Daisy Mae Converter it was demonstrated conclusively that intensively loaded two phase systems of bacteria and algae are feasible. Experiments with the microterella demonstrated that internally balanced systems of bacteria, algae, and metazoa (mice) are feasible. As a consequence of these findings, stress is now concentrated on the perfection of the various system components. Inasmuch as it is the key regenerator, the component that received the most intensive study during the past year was the algatron.

As a part of the studies, determinations were made of the type of modifications required for improving the performance of the algatron and the microterella, and evaluating the efficacy of those modifications after they were made. Modifications were made on the light chamber of the algatron to increase the light energy influx to the algal culture; on its

cooling system to increase the heat exchange capacity of the system; and an arrangement was made for measuring the rate of water reclamation in the algatron system. The mixing and effluent probes in the algatron were redesigned to accomplish their respective functions with a minimum of splashing. Modification of the microterella involved replacing the former culture system with an algatron system.

The experimental work consisted principally in studies aimed at evaluating the performance potential of the algatron system and ascertaining the effect of variations in common environmental factors on the functioning of the system with respect to oxygen production as indicated by algal yield, waste treatment, and water recovery. Design of a two-man unit was carried out as far as sizing the units and determining volumes and heat transfer information.

1.2 Conduct of the Investigation

The investigative work reported herein was carried on during the period 1 March 1964 to 28 February 1965 by the Sanitary Engineering Research Laboratory of the University of California, Berkeley, under contract AF 19(628)-2462 between the Air Force Cambridge Research Laboratories, Office of Aerospace Research and The Regents of the University of California.

2. MODIFICATION OF THE ALGATRON

2.1 Description of the Modified Algatron

Inasmuch as a detailed description of the algatron and an elucidation of the principles involved in its operation and function were given in the First Technical Report [1], only those modifications of the unit made for carrying out the experimental work are discussed in this report. The first modification was the coating of the interior and exterior surfaces of the light chamber with a whitewash composed of magnesium oxide suspended in water. The coating increased the light intensity at the culture surface by 30 per cent to 50 per cent. Magnesium oxide was selected because of its high degree of reflectivity and its ease of application, removal, and renewal. The latter two characteristics are important because of the relatively rugged conditions encountered during the experimental work. Frequently a minor mishap will cost the

interior surface of the chamber with displaced culture. For the light chamber to serve its purpose, the interior must be cleaned and the reflective surface renewed after each such mishap. If a metallic mirror-type coating were used, the repeated cleaning (necessary under present conditions) would result in a rapid loss of reflectivity due to unavoidable etching and abrasion. The disadvantages resulting from the loss of time and from the amount of expense involved in renewing such a surface outweigh the advantage of any superior reflectivity.

A second modification was the installation of a permanent condensing heat exchange system. The permanent system consists of 30 meters of aluminum tubing (outer diameter, 9.5 mm) in a vertical coil 61.2 cm in diameter and with 1-cm spacing between each spiral. The specific surface of the tubing is 3 sq cm per cm of length. Hence, the total surface area of the exchanger is 0.9 sq m. The position of the condenser in the light chamber is shown by the diagram in Figure 1.

A third modification was the installation of a water collection device with which the rate of condensation on the cooling coil could be determined. The device consisted of a beaker suspended below the discharge tube of the cooling coil and attached to a length of nylon cord in such a manner that it could be tilted to exclude water or positioned to collect water without opening the light chamber.

A fourth modification was an increase in the light energy source through the installation of five iodine vapor lamps (General Electric Quartzline 500 watts) in the main light bank under the light chamber, and suspending a 30-watt circular fluorescent lamp inside the drum. The intensity of the illumination at various locations in the algatron as the number and position of lamps were changed is given in Table I. The positions of the light sensing probe at which light intensity determinations were made are shown by the diagrammatic sketch in Figure 2. In position 'a' in the figure, the probe is sensing light being transmitted through and also reflected from the culture. In position 'c' the sensor is receiving light from the light source before the light impinged upon the culture; in other words, it is a measure of the light intensity at the culture surface. Determinations of light intensity were made with the drum remaining stationary (no culture film between probe and light source) and moving (culture between probe and light source). The

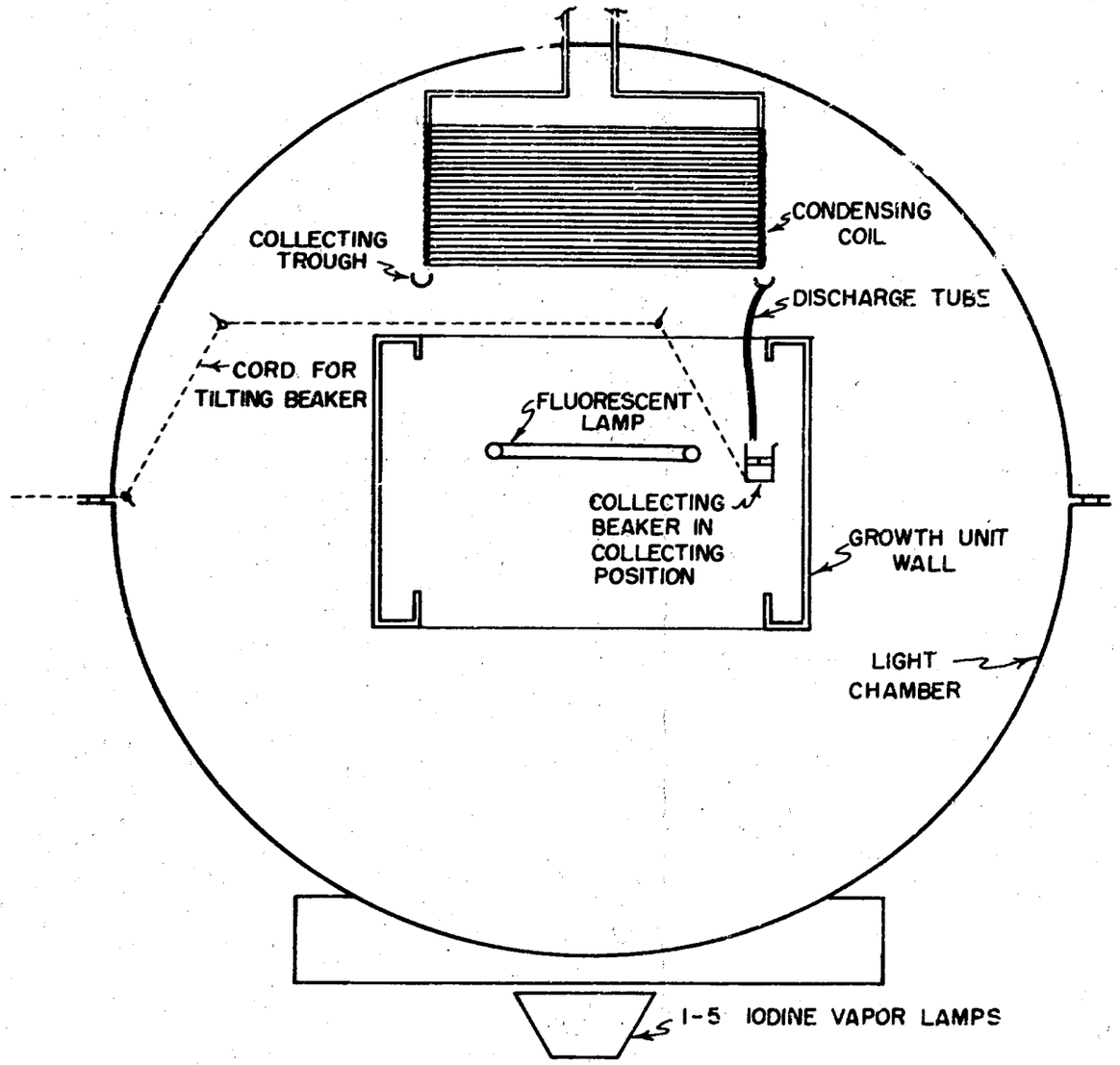


FIGURE 1. HEAT EXCHANGER AND WATER COLLECTION DEVICE

TABLE I

LIGHT INTENSITIES AT THE SURFACES OF THE CULTURE

Number of Lamps		Probe Position[a]	Drum Motion[c]	Light Intensity (ft-candles)
Bottom Source[a]	Inside Drum[b]			
1	0	a[d]	+	6
1	1	a	+	8
1	0	a	–	40
1	1	a	–	60
4	0	a	+	26
4	1	a	+	23
4	0	a	–	200
4	1	a	–	220
5	0	a	+	30
5	1	a	+	26
5	0	a	–	225
5	1	a	–	220
1	0	b[e]	+	22
1	1	b	+	24
4	0	b	+	57
4	1	b	+	60
5	0	b	+	72
5	1	b	+	77
1	0	c[f]	+	4
1	1	c	+	310
1	0	c	–	10
1	1	c	–	330
4	0	c	+	200
4	1	c	+	500
4	0	c	–	230
4	1	c	–	550
5	0	c	+	220
5	1	c	+	500
5	0	c	–	270
5	1	c	–	550
1	0	d	+	36
1	1	d	+	40
4	0	d	+	200
4	1	d	+	210
5	0	d	+	230
5	1	d	+	230

[a] 1-5 General Electric Quartzline lamps (iodine vapor), 500 watts each.

[b] One circular 30-watt fluorescent lamp (daylight).

[c] Drum revolving: + ; drum stationary: – . Culture spreads as thin film on wall when the drum revolves.

[d] Probe facing culture on inside of drum when latter two are revolving (Figure 2, position a).

[e] Probe facing culture on outside of drum when latter two are revolved (Figure 2, position b).

[f] Probe not facing the culture (Figure 2, position c).

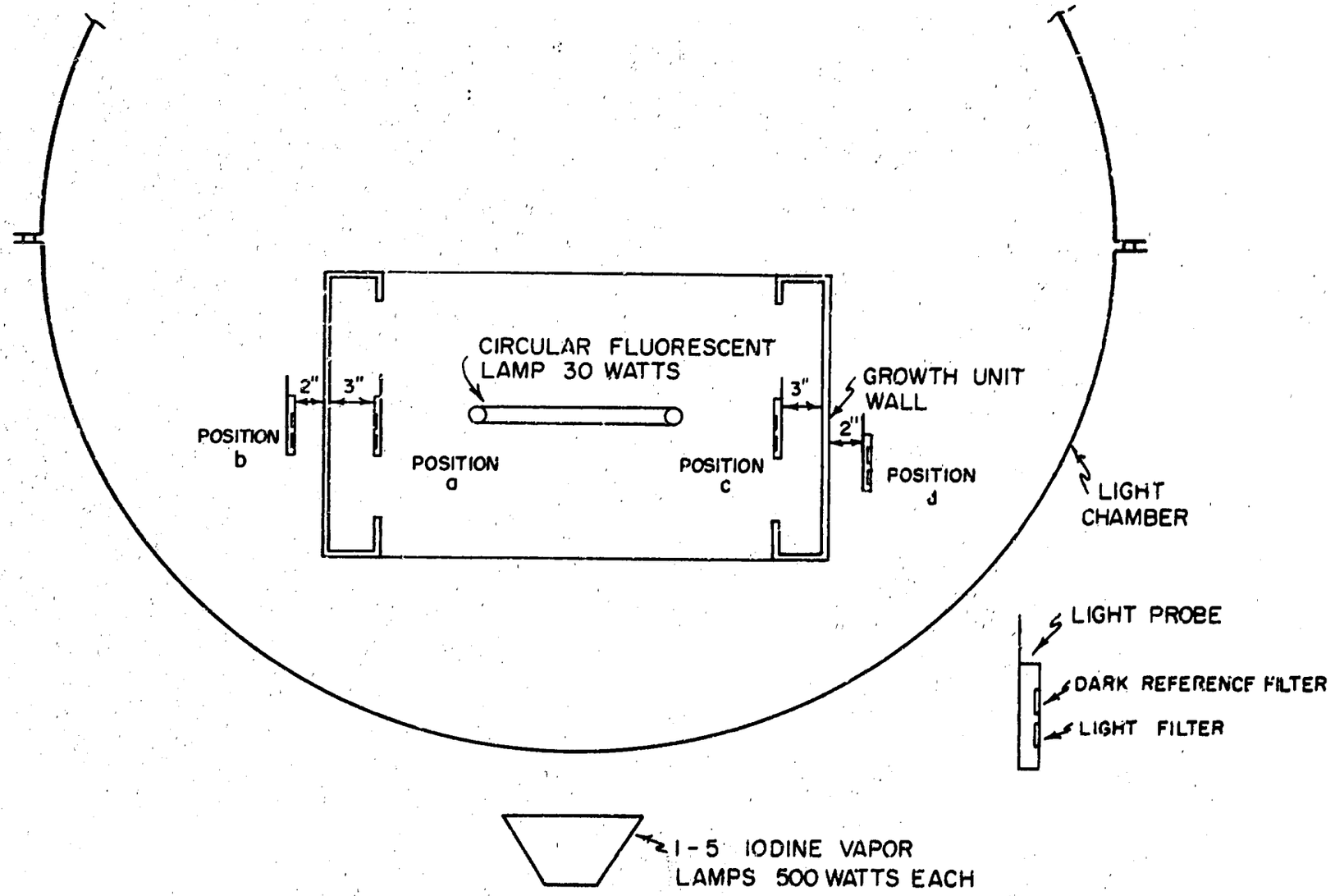


FIGURE 2. ARRANGEMENT OF LIGHT PROBE FOR LIGHT MEASUREMENT

difference between the latter and the former represents the drop in intensity due to light absorption by the culture (concentration 3000 mg/l). As the data in the table (position 'c') indicate, the single interior circular 30-watt fluorescent lamp supplied more light, as far as the culture was concerned, than did the five external lamps combined. Thus, the light intensity at the surface of the culture inside the drum was only 220 ft-c with all 5 bottom lamps on; whereas when the fluorescent lamp was on, the intensity was increased to 500 ft-c. The reason for the disparity is that most of the light energy from the bottom is lost before it reaches the culture surface. In a more effective light chamber, this loss would be materially reduced. The light intensity at the outside surface of the drum was appreciably less than that at its inside surface, as is indicated by the difference in values listed in Table I for positions 'c' and 'd.' Because of absorption by the plastic wall, the actual light intensity at the culture surface facing the drum wall was only from 60 per cent to 75 per cent that of the values listed for light intensity at 'd.'

3. EXPERIMENTAL WORK

3.1 Introduction

The experimental work during the year 1964-65 was concerned with determining the algal yields, the extent of removal of organic materials and nutrient salts, and the amount of water recovery that could be obtained under various environmental conditions with the use of the algatron.

3.2 Yield

a. Procedure. Variables studied in the experiments on yield included light intensity, detention period, CO_2 concentration, and algal type. The experiments concerned with the effect of light intensity under the conditions prevailing in the light chamber were completed prior to the installation of the interior lamp. In experiments concerned with the effect of detention period, certain difficulties were encountered that arose because of the centrifugal field that is an essential feature of the algatron. The difficulties were those concerned with providing the continuity of removal of algal cells from the algal culture that is

needed for maintaining a continuous culture. Because of the centrifugal field, some of the algal cells gathered into a film on the algatron wall, and this film gradually increased in thickness until at the end of a 24-hour period an appreciable portion of the culture was adhering to the drum wall. Consequently, as more of the cells became attached to the wall, the fewer were those discharged with the effluent. As a result, the effluent concentration 24 hours after cleaning the drum wall usually was but a fraction of that discharged directly after cleaning. Such a situation could be alleviated some with the use of more than one mixing probe, or preferably with a "scanning" probe, i.e., one that would be slowly moved up and down the vertical wall of the revolving drum. Although characteristic adherence of the algae to the drum wall may have been somewhat of a nuisance in the conduct of the experiments on the effect of detention period, it would be a distinct advantage in waste treatment. Because of it, a system involving the use of an accelerated symbiotic biomass could be applied. In such a system, wastes are exposed to a highly concentrated suspension of symbiotic biomass (algae and bacteria in this case). The contact time of wastes with active organisms is brief, inasmuch as the number of organisms per unit mass of concentrated waste is large at any given instant.

In the experiments, detention periods were imposed by discarding not only those cells contained in the effluent being discharged from the algatron, but also (after stopping the algatron) a portion of the mass adhering to the drum wall, and at times, a portion of those in the culture reservoir. However, complete uniformity in the length of the detention period of the algae could not be maintained since the amount of algae removed each day from the algatron wall varied. Deposition of algae on the drum wall ranged from 3.5 grams (dry wt) to as much as 6 g. Because of the tendency of some of the algae to cling to the algatron wall and since the algal mass had to be removed manually, the shortest detention period for the biomass was on the order of one day. Detention periods for the liquid phase were varied from 6 hours to 48 hours.

The study on the relation between algal type and yield with the algatron was concerned with two types of algae, namely, Chlorella sp. and Oscillatoria sp. During the early stages of the study on the relation between detention period and yield, when only those algae that

were discharged with the effluent were removed from the system, a gradual buildup of a species of Oscillatoria was noted. Because a corresponding increase was noted in tendency of all algae in the culture to settle with increase in Oscillatoria concentration, and inasmuch as this characteristic would be useful in waste treatment, it was decided to allow the algae buildup to continue. When Oscillatoria sp. became the predominant species, then tests were made that were similar to those carried out when Chlorella sp. constituted the principal species.

Two levels of CO_2 concentration, 1 per cent and 2.5 per cent, were tried in the experiments on yield. These levels were maintained by discharging pure CO_2 into the light chamber at 0.05 and 0.13 cu ft/hr, respectively. A medium consisting of sewage enriched with urea (200 mg/l) and two different synthetic media were used. The first synthetic medium, designated "nitrate medium" in this report because of its nitrogen source, consisted of 1.2 g KNO_3, 2.5 g $MgSO_4 \cdot 7H_2O$ and 1.25 g KH_2PO_4 per liter. To this were added iron and trace elements in the concentrations recommended by Arnon [2]. The second synthetic medium, termed "Urea medium" in this report, contained 0.5 g each of urea, $MgSO_4 \cdot 7H_2O$, and KH_2PO_4 per liter, and in addition, iron and trace elements at one-half the concentration prescribed by Arnon.

Yield was determined on the basis of dry weight of algal-bacterial biomass. (The algal-bacterial biomass consistently was from 98 per cent to 99 per cent in the form of algae.) Problems that made difficult the imposition of a detention period on the biomass also complicated the determination of the daily yield. Therefore, a method had to be devised for collecting and determining the dry weight of those algae which adhered to the algatron wall. This was accomplished by carefully collecting the material with a 6 x 3 x 2 inch cellulose sponge. The greater part of the mass gathered on the sponge with each pass was scraped into a Waring blendor by means of a small stainless steel spatula. Algae carried into the sponge pores were displaced into the blendor by repeatedly soaking the sponge with distilled water and squeezing it. The suspension was blended and poured into a volumetric flask, then brought to a desired volume by adding distilled water. Aliquots were centrifuged and the dry weights were determined. Aliquots of the effluent and, when necessary, of the culture remaining in the algatron also were centrifuged and their dry weights determined. Unless otherwise specified, each experimental run was of 3 weeks' duration--two for attaining "steady state" and one for collecting results. Data listed in the tables are an average of the last week's data.

b. Results. In the first two runs, Chlorella was the predominant algal type. Very few algae clung to the drum wall, and hence difficulties arising from wall accumulations were not encountered. Therefore, in these two runs, liquid and suspended solids detention periods were practically identical, and yields could be estimated on the basis of biomass discharged with the effluent.

In the first run, three lamps were used as the illumination source. With this number of lamps, light intensity at the outside surface of the culture (surface facing the drum wall) was about 150 ft-c; and that at the inside surface (surface facing the interior of the drum), 165 ft-c. Three detention periods, 1.6, 1.0, and 0.75 days were applied. In the second run, four lamps were used (light intensities at the inside and outside surfaces, 230 and 200 ft-c, respectively), and the detention periods were 1.8, 1.0, and 0.75 days, respectively.

Average results obtained in the two runs are listed in Table II. In later runs, even though Chlorella continued to be the predominant type, algae accumulated on the drum wall, and hence the procedure was followed for determining yield that was described earlier. Results obtained with Chlorella are listed in Table II. According to information in Table II, the daily yield increased as the number of lamps increased, and therefore light intensity at the culture surface was greater. Shortening the detention periods also brought about an increase in yield. No distinction could be made concerning the relative importance of cell detention period with that of the liquid phase on the basis of the data in Table II, since the detention periods of both were shortened simultaneously in each run. However, at hydraulic detention periods less than 0.75 day, in experiments concerned with the removal of organic substances and nutrient salts, the cell detention period was more important in influencing daily yield, provided sufficient biomass accumulated on the algatron wall to permit the maintenance of a cell detention period of at least 0.75 day. According to the data in Table II, the highest average yield, 1497 mg/l/day, was attained when the light intensities at the two culture surfaces were 225 and 270 ft-c, respectively; the detention period for the liquid phase at 0.75 day; and that of the biomass, 0.97 day.

The relation between yield and type of media is indicated by the data listed in Table III. The values given for growth on sewage medium

TABLE II

EFFECT OF DETENTION PERIOD AND LIGHT INTENSITY ON YIELD

Lamps (No.)	Light Intensity (ft-candles)		Detention Period (days)		Average Concentration of Culture[d] (mg/l)	Algae on Wall (g)	Average Concentration of Effluent (mg/l)	Average Yield (mg/l/day)
	Inside[a]	Outside[b]	Liquid	Biomass[c]				
3	165	150	1.6	1.6	490	--	490	306
3	165	150	1.0	1.0	360	--	360	360
3	165	150	0.75	0.75	315	--	315	420
4	230	200	1.8	1.8	1327	--	1327	737
4	230	200	1.0	1.0	994	--	994	994
4	230	200	0.75	0.75	944	--	944	1258
5	270	225	1.0	1.2	1306	3.03	630	1285
5	270	225	0.75	0.97	1463	2.60	751	1497

[a]Surface facing inside of algatron drum. [b]Surface pinned against drum wall.

[c]Approximate--see text. [d]Capacity of algatron — 6.18 liter.

TABLE III

YIELDS WITH THE USE OF SYNTHETIC MEDIA AND WITH SEWAGE MEDIA

Medium	Detention Period (days)		Average Concentrated Culture (mg/l)	Algae on Wall (g)	Average Concentrated Effluent (mg/l)	Average Yield (mg/l/day)
	Liquid	Biomass				
Nitrate[a]	0.75	0.85	667	b	590	790
Urea[c]	1.0	1.55	1723	3.61	231	1109
Sewage[d,e]	1.0	1.2	1463	2.60	630	1285

[a]Synthetic medium in which KNO_3 was the nitrogen source.

[b]Algae that accumulated on wall was brushed back into the culture.

[c]Synthetic medium in which urea was the nitrogen source.

[d]Settled sewage enriched with urea at 200 mg/l.

[e]Data from Table II--one-day detention period.

are those for the 5-lamp, 1-day liquid and biomass detention period in Table II. Data for the 1-day detention period were selected because that detention period was the one at which the culture was operated during the experiments with the nitrate and the urea media. The daily yield was quite low, viz., 790 mg/l/day, when the nitrate medium was used. The culture was a yellowish green in color, and in general did not respond favorably to the medium. On the other hand, growth was quite vigorous in the urea medium and the culture had a deep green color. Highest yield, 1285 mg/l/day, was obtained with the use of the enriched sewage medium. Since these results coincide with those obtained by the authors in previous studies [3,4] in experiments in which other types of growth units were used, it may be concluded that growth in the algatron system does not alter the nutritional requirements of algae.

In the experiments in which Oscillatoria sp. constituted the predominant algal group, light was not varied and five lamps were used throughout. However, the detention period of the liquid phase was varied from 6 hours through 24 hours. Regulation of the detention period of the biomass was very poor in the runs with this organism because of the problems involved in obtaining representative samples of the culture biomass without losing the culture. The difficulty was due to the extreme tendency of the Oscillatoria filaments to agglomerate into rapidly settling masses in which practically all of the other algae were trapped, thus settling out of suspension. In one attempt, the culture was mixed in a Waring blender, an appropriate amount discarded, and the remainder was returned to the algatron in the amount that would result in a 0.75-day detention period for the cells. After 2 days of such treatment, the Oscillatoria disappeared almost completely. However, they regained their ascendancy when cellular removal was confined to that clinging to the algatron wall and to the small amount discharged with the effluent. Detention period of the liquid phase, within the range tried, had no effect on daily yield. Average yield was 1435 mg/l/day, or about the same as that obtained with Chlorella. The principal difference between the two types of cultures, i.e., Oscillatoria and Chlorella, was that a swampy odor, generally repugnant to humans, was noticeable upon opening the light chamber when Oscillatoria were being cultured. This odor was not noticeable when Chlorella was the most abundant organism.

c. Discussion. Results obtained from the entire series on yield point to the fact that light was the key limiting factor for algal growth in the algatron. This was most obviously demonstrated by the increase in yield that accompanied increase in light intensity at the culture surfaces. Less obvious was the fact that yield also was favorably affected when the detention period of the biomass was shortened. Although a large part of the favorable yield accompanying the use of short detention periods may stem from the maintenance of the cells in the log phase of growth, an appreciable fraction may have been due to a reduction in culture density, and hence greater degree of light penetration. Or, since the amount of available light at any point and instant was sufficient for a given number of cells, this light could be extended, so to speak, by increasing the number of cells contacting at that point by increasing the rate of turnover of cells, i.e., shortening the detention period of the biomass.

The low yields with the nitrate medium in comparison to those with urea and sewage may have been due to two factors: one, the nitrogen in nitrate may not be as readily available to the algae as that in urea or in sewage; and two, the overall salt concentration may have been too high in the nitrate medium. In the first run with the urea medium, $MgSO_4 \cdot 7H_2O$, KH_2PO_4, trace elements, and iron were added in the concentrations prescribed for the nitrate medium; nitrogen was introduced in the form of urea at one-half the concentration of nitrogen in the nitrate medium. Although yield was somewhat higher than that with the nitrate medium, the yellowish green color of the culture indicated that growth was not at its maximum. Reducing the concentration of all of the constitutents to the level given under "Procedure" brought about an increase in yield to the level indicated in Table III. Apparently enriched sewage has the algal nutrients in the concentration and proportions best suited for growth, inasmuch as yields with it were consistently higher than with the other media.

The experiments demonstrated that an Oscillatoria type alga would be distinctly useful in the application of the algatron system. Its usefulness arises from the extreme tendency of the filaments to aggregate in an undisturbed culture. Within minutes in an Oscillatoria-predominated culture, all of the algae, planktonic and otherwise, will have settled out of the culture. These clumps not only include the filamentous

Oscillatoria, but also the planktonic algae which apparently are screened out of suspension and entrapped by the filaments of Oscillatoria as the latter aggregate. These clumps are sufficiently stable to withstand breaking up by filtering, a feature which would be advantageous in a gravity-free environment. The tendency of the algae to aggregate and to cling to the rotating wall of the algatron makes it possible to apply extremely short detention periods to the liquid phase of the culture, and hence to increase the capacity of the unit for waste treatment. In effect, an accelerated symbiotic biomass is established in which the ratio of biomass to liquid receiving treatment can be maintained at an optimum level. Maintaining such a ratio is not always possible with planktonic algae even in an algatron because of the difficulty in providing an appropriate concentration of biomass at short hydraulic detention periods.

A possible disadvantage in the use of filamentous algae such as Oscillatoria might be the lower yield that one usually expects of filamentous algae. However, under conditions made possible by the algatron, the daily yield with Oscillatoria was practically as great as with Chlorella. The high yield attainable in the algatron is due in great part to the fact that algae, filamentous or not, are pinned against the rotating wall as a thin omnilaterally illuminated layer bathed by a continuously mixed and changing medium and directly exposed to the gaseous environment. Therefore, light and nutrient (solid or gaseous) are immediately available. Thus, the filamentous algae enjoy those advantages which are available to planktonic forms by reason of the large surface-to-volume ratio of the latter.

A definite disadvantage of the use of Oscillatoria, however, is the vaguely unpleasant odor that emanates from the culture. As stated before, the odor is reminiscent of a stagnant swamp. Another disadvantage, although perhaps only apparent at this time, is the ease with which Oscillatoria can be lost. However, when this occurs, planktonic forms increase as the Oscillatoria disappear, so that at no time is there a net loss of photosynthetic biomass. The ease with which Oscillatoria can be lost undoubtedly is due to our incomplete knowledge of the care of Oscillatoria cultures. We are certain, however, that one or two exposures to homogenization in a blendor will ensure the loss of an Oscillatoria culture. Therefore, in experiments involving the culture of the organism,

one must sacrifice accuracy in determining the dry weight of a given culture or otherwise risk losing the culture in attempting to secure a completely representative sample needed for a dry weight determination. The loss of Oscillatoria after blending probably was due not only to injury to the constitutent cells brought about by fractionating the filaments, but also by the short detention period resulting from the increased discharge of homogenized material with the effluent.

The experiments on yield demonstrated the great potential of the algatron system in oxygen production, since even under the adverse light conditions prevailing in the light chamber a yield of 1.5 g/l/day could be obtained. Using this conservative figure as a basis and multiplying by 1.6 g to arrive at an estimate of oxygen production, we find that the greatest estimated oxygen production in the algatron under the conditions prevailing in the experiments was on the order of 27.2 g/sq m of drum wall. Even at this low production rate, the required drum surface area per man would be from 20 to 25 sq m. A more effective means of dispersing and channeling light energy to the culture surface would undoubtedly have resulted in yields greatly in excess of those attained in the experiments, and hence a corresponding increase in the oxygen yield per unit area of drum wall.

3.3 Removal of Dissolved Organic and Inorganic Substances

a. Procedure. In each run, the algatron was operated under the experimental conditions for a period of a week or unitl a "steady-state" was reached. At the end of this period, samples were collected and analyses were made on each of the succeeding four days. Data as listed in the tables concerned with removal are the averages of results obtained on these four days.

The principal variable applied in this series of experiments was detention period. Two types of media were tried; namely, sewage enriched with urea (200 mg/l) and unenriched sewage The number of lamps used in the illumination source was five. Hence, the light intensity on the inner and outer surfaces of the culture were 270 and 230 ft-c, respectively. Unless otherwise stated, Chlorella constituted the major portion of the algae population.

Samples were prepared for analysis by removing an aliquot of effluent, centrifuging it at approximately 500 x g for 10 minutes and

reserving the supernatant for analysis. Routine tests were made of the algae-free supernatant for BOD, volatile and total dissolved solids, PO_4-P, Mg, Ca, and N according to methods described in Standard Methods [5].

b. Results. Estimates of removal of organic matter were based on the extent of reduction of BOD and on the amount of volatile dissolved solids in the influent to the algatron. Change in BOD indicates a change in the amount of readily decomposable organic matter, while a change in the volatile dissolved salts is a measure of the disappearance of total organic matter, since the greater part of the volatile dissolved substances, as determined according to Standard Methods, are organic in nature.

The average concentrations of influent and effluent dissolved organic and inorganic constituents at various biomass and liquid detention periods are given in Table IV. Percentage removal of each of these constituents is shown in Table V.

Regardless of a variation in average influent BOD ranging from a low of 73 mg/l to a high of 154 mg/l, the effluent BOD values were within the range of 5.5 to 11.1 mg/l. The degree of variation in volatile dissolved solids concentration of the effluent was somewhat greater, ranging from 59 mg/l to 119 mg/l, although the variation in percentage of the total dissolved solids as volatile was less extensive, ranging from 21 per cent to 33 per cent. In general, a high volatile dissolved solids concentration in the effluent paralleled or accompanied a high volatile dissolved solids concentration in the influent. Phosphorus removals of as high as 45 mg/l were observed, although generally the removal varied from 8.5 to 35 mg/l. The higher removals characteristically followed high initial concentrations. An average of from 16 to 68 mg/l of NH_3-N were removed during the various runs. As with PO_4-P, the amount of NH_3-N that was removed was dependent upon the amount initially present. Thus, when the average initial concentration was 101 mg/l, the extent of removal was 62 mg/l of culture. Difficulty was encountered in analyzing for total nitrogen, probably because urea is not readily digested in the kjeldahl process. It is very likely that all of the values for total nitrogen reported in Table IV are low.

TABLE IV

DISSOLVED ORGANIC AND INORGANIC SOLIDS CONCENTRATION OF THE INFLUENT AND EFFLUENT

A. Conditions

Run	Medium[a]	Detention Period (days)		Culture Solids		
		Liquid	Biomass	Culture (mg/l)	Wall (g)	Effluent (mg/l)
1	a	1.0	1.7	1780	2.34	690
2	b	0.75	3.1	2122	1.11	346
3	a	0.50	1.9	1434	4.29	56
4	b	0.50	3.0	2110	1.41	246
5	a	0.25	3.0	1802	2.74	51
6	b	0.25	6.1	2147	1.31	40

B. Influent

Run	BOD (mg/l)	Dissolved Solids (mg/l)		PO_4-P (mg/l)	Mg (mg/l)	Ca (mg/l)	Nitrogen (mg/l)	
		Total	Volume				NH_3	Total
1	154	328	118	46.5	20.0	23.0	76.5	119
2	150	409	180	52.5	14.6	23.6	21.6	-
3	73	371	141	22.7	21.2	32.8	105.1	101
4	81	394	191	15.5	24.9	48.4	37.4	-
5	123	450	208	51.9	19.7	36.0	101.2	-
6	71	304	111	9.5	26.8	31.4	16.9	17

C. Effluent

1	8.7	312	85	0.6	16.1	19.0	8.3	28.2
2	11.0	331	111	16.9	10.8	20.2	2.4	11.2
3	9.3	336	86	3.4	20.7	28.0	47.1	41.4
4	10.0	355	119	0.7	18.7	42.1	0.0	5.4
5	11.1	284	59	28.5	11.1	31.6	39.3	-
6	5.5	283	86	1.0	25.6	31.1	0.7	1.0

[a]Medium: a--sewage plus urea (200 mg/l); b--sewage only.

TABLE V

PER CENT REMOVAL OF ORGANIC AND INORGANIC DISSOLVED SOLIDS AS A FUNCTION OF DETENTION PERIOD

Biomass[a] Concentration (g/l)	Detention Period (days)		Removal, (%)							Stability	
	Biomass	Liquid	BOD	Volatile Dissolved Solids	PO_4-P	Mg	Ca	NH_3	Total N	Factor[b]	Increase[c] (%)
2.124	1.7	1.0[d]	94	28	99	4.3	17	89	76	0.102	92
2.064	1.9	0.5[d]	88[e]	48	85[e]	24.0	15	55	56	0.108	79[e]
2.285	3.1	0.75[f]	93	38	68	2.6	14	89[e]	--	0.099	88
2.317	3.0	0.5[f]	87[e]	38	95[e]	32.8	13	100[e]	--	0.084	80[e]
2.204	3.0	0.25[d]	91	71	45	43.0	12	61	--	0.188	68[e]
2.339	6.1	0.25[f]	91	22	89[e]	12.0	1	90[e]	98[e]	0.064	90

[a]Culture plus wall algae.

[b]Stability factor: BOD/Volatile Dissolved Solids.

[c]Influent stability factor--effluent stability factor/influent stability factor x 100.

[d]Medium: sewage plus urea (200 mg/l).

[e]Low initial value.

[f]Medium: sewage only.

According to the data in Table V, the actual average total amount of biomass in the algatron did not vary more than about 13 per cent regardless of length of detention period of liquid or of the cells. As reported in the Table, total biomass includes the algae on the wall and those in the culture at the time samples of each were removed for analysis. The solids contained in the culture sample are those carried down with the liquid into the culture reservoir when the algatron drum is stopped for removal of the sample. When the drum is rotating, this biomass is combined with that which clung to the wall while the drum was stationary and the two constitute the total biomass contained in the film on the drum wall, i.e., the active material to which the incoming liquid medium is exposed.

As the data in Table V indicate, percentage BOD reduction ranged from 87 per cent to 94 per cent. Percentage removal of influent BOD, as is indicated by the data, was relatively uniform at all of the detention periods tried in the table. It should be noted that the lower percentage reductions in BOD, namely 87 per cent to 88 per cent, took place in the runs in which the initial BOD also was lower than those in which the per cent reduction was greater.

The highest per cent removal of dissolved volatile solids (71 per cent) occurred when the detention period for the biomass was 3 days; and that for the liquid, 0.25 day. However, no relation between the remaining combinations of detention period and percentage removal was observed. The formula used for obtaining the values used to express per cent increase in stability is given in Table V. It is based on the assumption that by relating volatile dissolved solids to BOD, an approximation can be made of the relative stability of those solids [4,6]. Effluents produced in those runs in which the medium was not enriched with urea had average stability factors of less than 0.1; whereas those from runs in which urea was used were about 0.1. The increase in average stability as determined by the formula given in Table V (footnote c) ranged from 68 per cent to a high of 92 per cent. The lower averages occurred in those runs in which the stability factor of the incoming dissolved solids was relatively low.

Phosphorus removal averaged from 45 per cent to 99 per cent. Within the conditions of the experimental runs, no relationship can be

detected between extent of removal and length of detention period either of biomass or of liquid. Unlike BOD removal and increase in stability, lower percentage values for PO_4-P removal were not due to a lower influent concentration. The two highest removals, 95 per cent and 99 per cent, occurred when the influent concentrations were 47 and 16 mg/l, respectively; and the lowest, 88 per cent and 87 per cent, when the influent concentrations were 23 and 52 mg/l. A wide fluctuation in per cent removal of Mg, namely 3 per cent to 40 per cent, was observed. As with PO_4-P, the data give no evidence of a relation between Mg removal and detention period of biomass or of liquid. Calcium removal was most extensive, 17 per cent, when the biomass detention period was only 1 day; and least, 1 per cent, when the biomass detention period was prolonged to 6.1 days. From 55 per cent to 89 per cent of the ammonia-nitrogen was removed from media consisting of sewage enriched with urea. When urea was not added to the sewage, ammonia-nitrogen removal ranged from 89 per cent to 100 per cent. In all cases initial concentration of ammonia-nitrogen seemed to be more decisive in extent of removal than did detention period of biomass or of liquid.

c. Discussion. Because of the relative uniformity in amount of total biomass present in the algatron throughout the entire series of experiments concerned with the removal of dissolved solids, had any change in extent of removal of dissolved solids taken place, it could have been attributed to variations in detention period. (The widest fluctuation in total biomass from run to run was only about 13 per cent.) Apparently, the range of detention periods applied in the study was not great enough to bring to light any such changes. The experiments did demonstrate that most of the readily decomposable organic dissolved solids can be stabilized with relatively short exposures to the algal-bacterial stabilization system in the algatron. This was shown by the drastic reduction in the amount of BOD of the incoming wastes, and by the low BOD of effluents at all of the liquid detention periods tried. In fact, even at the 0.25-day detention period, the BOD of the effluent was only 5.5 mg/l. Further evidence of the rapidity of stabilization is the low value of the stability factors of the effluent, especially in those experiments in which unenriched sewage was used as the medium. The higher stabilization factors of the enriched sewage may have been due

to the presence of unused urea or ammonium salts constituting the breakdown products of urea. These compounds are volatilized in the combustion furnace and are included in the volatile fraction of the dissolved solids; thus the nitrogen may be available to the bacteria used in the BOD analyses. Inasmuch as the reduction in BOD and increase in stability of the volatile dissolved salts continued unabated at their high levels even at the 0.25-day detention period, the minimum exposure time at which adequate treatment can take place must be considerably shorter than the 0.25-day period.

The ability to apply very brief detention periods to the liquid wastes in the algatron without loss of culture concentrations increases the utility of the algal-bacterial environmental control system. This advantage is enhanced by the fact that the operation is accomplished without the penalty of added power and light requirements. Operational characteristics making short hydraulic detention periods permissible are the centrifugal field set up by the rotating algatron and the instant mixing accomplished by placing probes at strategic locations. A differential separation is possible because the algae, though pinned against the algatron wall as a thin layer, nevertheless are kept in suspension in that thin layer by the mixing action of the probes. As a result, the liquid continuously moves through the algal layer without carrying away with it the entire mass of algae contained in the layer. The centrifugal force applied by the algatron is not so great that separation of the algal from the liquid phase is complete, hence some cells are carried out with the effluent. The mixing probe also ensured the displacement of some cells with the effluent. This displacement feature is essential, otherwise a detention period could not be applied to the biomass without unduly complicating the process. Our experience with the present model of the algatron indicates the desirability of a "scanning" type of probe, i.e., a probe which moves up and down.

The saving in power and weight that results from using the algatron system in accomplishing the differential movement of biomass and liquid is due to the fact that all of the power requirements for accomplishing separation, mixing, gas exchange, and discharge of effluent are met by a single unit of power supply, namely that used to rotate the algatron. Moreover, the substitution of a rotating drum for a revolving

rotor in conjunction with a stationary drum (i.e., a centrifugal pump) transforms the applied power to the potential energy of the lifted liquid and thereby minimizes losses arising from friction. In addition, the gradual travel of the liquid through the drum is practically laminar and the only turbulence is that deliberately brought about with the use of mixing probes designed according to hydrodynamic principles.

Although rapid removal, i.e., stabilization of the organic constituents of wastes, is a desideratum in a closed system, the loss of certain nutrient salts in a biologically enclosed system is not, since these nutrients must then be replaced from an outside source. Therefore, this fact should be kept in mind when interpreting the results concerned with the removal of PO_4-P, Mg, Ca, and N. Unlike the practice in terrestrial waste treatment, those conditions should be fostered that result in the loss of only the amount of nutrient that is assimilated by the biomass. The reason for emphasizing this point is that in photosynthetic systems conditions of light and temperature and resulting growth rate of algae may be such as to alter the ratio of H^+ to $(OH)^-$ in the medium to the extent that precipitation of certain elements such as PO_4-P, Mg, and Ca is accomplished. Such conditions should be avoided to ensure efficient utilization of the nutrients. The average amounts of these elements assimilated by the biomass in a liter of culture and the losses by precipitation are listed in Table VI. According to the data, an excess of phosphorus over that required to support the algal growth attained under the conditions of the experiment was present in all of the runs. Moreover, in all of the runs some of this excess was lost by precipitation, and the actual amount thus lost increased in proportion to the excess. For example, in runs 1 and 2 the initial concentrations of phosphorus were 46.5 and 22.7 mg/l, respectively. The losses in mg/l by precipitation were 28 to 34 mg/l and 3 to 9 mg/l, respectively. The two values for each initial concentration are based on the reported minimum and maximum phosphorus content of algal cells. This holds true even at low initial concentrations when the assimilatory rate is low in proportion to the amount of phosphorus available; as was the case in run 6, in which only 4 to 6 mg of phosphorus were incorporated into algal material, whereas the amount of available phosphorus was 9.5 mg/l. Therefore, to procure the most effective use of phosphorus, a dosage should be used that approximates the expected demand as closely as possible.

TABLE VI

REMOVAL OF DISSOLVED NUTRIENT ELEMENTS BY ASSIMILATION AND BY PRECIPITATION

Run	Detention Period (days)		PO_4-P			Mg			Ca		
	Biomass	Liquid	Biomass[a] (mg/l)[c]	Precipitated[b] (mg/l)[d]	(%)[e]	Biomass[a] (mg/l)[c]	Precipitated[b] (mg/l)[d]	(%)[e]	Biomass[a] (mg/l)[c]	Precipitated[b] (mg/l)[c]	(%)[e]
1	1.7	1.0	12-18	28-34	63-74	3-19	1-17	6-12	0-19	0-4	0-21
2	1.9	0.5	10-16	3-9	13[d]-40[d]	3-19	0	0	0-17	0-5	0-15
3	3.1	0.75	7-11	25-29	48-55	2-11	0-2	0-14	0-11	0-3	0-14
4	3.0	0.5	7-12	3-8	19[d]-52[d]	2-12	0-4	0-9	0-12	0-6	0-13
5	3.0	0.25	7-11	12-16	23-69	2-11	0-7	0-35	0-11	0-4	0-12
6	6.1	0.25	4-6	3-5	31[d]-53[d]	1-6	0-0.2	0-1	0-6	0-0.3	0-1

[a]Based on percentage of the element in Chlorella as reported by Scott [7].

[b]Precipitated: Influent PO_4-P—Biomass PO_4-P.

[c]Mg/l of culture.

[d]Mg/l of influent.

[e]Precipitated PO_4-P/Influent PO_4-P x 100.

The tendency of Mg and Ca to precipitate apparently was not as great as that of phosphorus, as is indicated by the high concentrations of Mg and Ca remaining in the effluent (cf. Table IV), and (even assuming that the low estimate of the biomass concentration of the elements is the true one) by the relatively low percentage of the material that was lost by precipitation. Because of the wide variation in the reported percentages of algal cells in the form of these elements (e.g., Mg, 0.26 per cent to 1.51 per cent; and Ca, 0.0 per cent to 1.55 per cent [7]), a generalization such as that given for the most efficient use of phosphorus cannot be applied to Mg and Ca on the basis of the experimental data obtained in the runs. Judging from the data on per cent removal of Ca as listed in Table V, the extent of removal increased with detention period of the algal cells. This fact would indicate that some Ca must be assimilated by the cells, since the daily yield of algae increased as biomass detention period was shortened, and hence if Ca is assimilated the removal due to this cause should be correspondingly increased.

If the biomass is assumed to have a nitrogen content of 7 per cent to 8 per cent, then, with the exception of run 6, all of the influent nitrogen that was removed was converted into cellular material in each of the liquid detention periods. In run 6, in which the biomass detention period was 6.1 days, only 52 per cent of the total nitrogen removal can be accounted for by cellular assimilation, even with the assumption of an 8 per cent nitrogen content--a percentage which would be rather high in view of the long detention period and consequent age of the cells. This unaccounted for nitrogen may have been lost by way of volatilization.

3.4 Water Recovery

a. Introduction. One of the more advantageous features of the use of the algatron system in a closed environment is the profuse production of low temperature (25°-30°C) distilled water as a by-product of the gas exchange and waste treatment phases of the system. Since the water is distilled at a low temperature, the more objectionable volatile substances found in human wastes are not carried over with the water vapor. Inasmuch as with the present setup in which the algatron is sealed in a light chamber, it is possible to maintain a constant temperature and relative humidity during an individual run, an excellent

opportunity was available for determining the rate of water recovery with the system.

There is the possibility that the presence of growing algae in a suspension may give rise to conditions that could increase the rate of evaporation beyond that normally to be expected at a given temperature and relative humidity. This increase could be brought about by the more effective absorption of light energy because the algal cells act as black bodies, i.e., absorb light energy and convert all but 1 per cent to 10 per cent of it to heat energy. Or, the increase in evaporation rate may be accomplished by a change in the surface tension of the water phase of the culture, a change that is brought about by the activity of the algae. These possibilities were also explored.

b. Procedure. The device for collecting the water from the cooling coil was described in the section on modifications.

In the study, three series of experiments were conducted. In the first series, the predominant solids in suspension consisted of algae; in the second series, carbon black constituted the predominant solids. In the third run, no suspended solids were present in the water. However, to account for any enhancement or inhibition due to the presence of dissolved salts, those salts used in making up the medium in which the algae were cultured were also added to the water in the second and third series. In each series, the number of lamps used was one, three, four, and five. Each series consisted of three experimental runs at each of the number of lamps tried. Each experimental run in a series was started by sealing the unit, i.e., closing the light chamber, either 5 hours or 16 to 18 hours prior to the initiating of water collecting. The collecting period varied from 80 to 150 minutes, its length depending upon the rapidity with which from 150 to 200 ml of water could be collected. The temperature and relative humidity prevailing inside and outside the light chamber were determined at the beginning and at the termination of each run. In the two series in which algae and carbon black were used, an attempt was made to keep the concentration of each comparable in their respective series. Algal concentration ranged from 2115 to 2625 mg/l, and that of carbon black was 2231 mg/l. (Cf. Table VII.)

TABLE VII

WATER RECOVERY

Suspension	Lamps[a]	Time Sealed[b] (hr)	Relative Humidity		Temperature (°C)		Suspended Solids (mg/l)	Average Collection Rate (ml/min)	Evaporation Heat Transfer[e] (cal/min)	Specific Heat Transfer[f] (cal/sq cm/min)
			In[c]	Out[d]	Begin.	End				
Algae	1	18	60	40	23	23	2625	1.45	856	0.145
Algae	1	6	50	40	24	24	2630	1.47	867	0.147
Algae	3	17	50	30	24	25	2115	1.71	1009	0.171
Algae	3	5	50	30	26	27	2115	1.99	1174	0.199
Algae	4	16	--	--	25	25	2590	1.72	1015	0.172
Algae	5	16	50	30	26	26	2590	1.93	1139	0.193
Algae	5	5	--	--	26	26	2590	1.98	1168	0.198
Carbon Black	1	18	60	40	23	23	2231	1.12	661	0.112
Carbon Black	3	17	55	30	24	24	2231	1.50	885	0.150
Carbon Black	4	5	50	30	26	26	2231	1.77	1044	0.177
Carbon Black	5	16	50	25	26	26	2231	1.91	1127	0.191
Carbon Black	5	5	50	35	27	28	2231	1.89	1115	0.189
Water[g]	1	16	60	40	23	23	0	1.36	802	0.136
Water[g]	3	17	50	30	24	24	0	1.53	903	0.153
Water[g]	3	5	50	40	26	26	0	1.73	1021	0.173
Water[g]	4	16	50	35	27	27	0	1.73	1021	0.173
Water[g]	5	16	50	30	27	27	0	1.83	1080	0.183

[a] 500-watt G.E. Quartzline (iodine vapor) lamps. [b] Time unit is sealed prior to collecting water.

[c] Relative humidity in light chamber. [d] Relative humidity of external environment.

[e] Water yield in ml/min x 590. [f] $H_s = Y_n \times 590/5900$. ($H_s$—cal/sq cm/min; Y_n—water yield in ml/min.)

[g] Water plus nutrient salts.

c. Results. Results obtained in the experiments are presented in Table VI. As one would expect, the water yield increased as the number of lamps was increased. The greatest difference in yield between the two suspensions and between the suspensions and the water alone was observed when only one lamp was used. At this light level, the yield per minute with the algal suspension was 1.45 ml (after the light chamber had been sealed for 16 to 18 hours); with carbon black, 1.12 ml; and with water only, 1.36 ml. As lamps were added, the rate of increase of evaporation from the carbon black suspension was greater than that from either the algae suspension or from water alone. With the carbon black, the rate of increase was about 0.20 ml/min for each lamp added to the initial one; whereas with the algae, it was 0.125 ml/min; and with water alone, 0.120 ml/min. As the data in Table VI indicate, yields were somewhat higher when collection was begun only 5 hours after the light chamber was sealed. Relative humidity in the light chamber ranged from 25 per cent (accuracy, ± 5 per cent) with 5 lamps in use to 40 per cent with 1 lamp. Temperature in the chamber varied from 23°C with 1 lamp to 26°-27°C with 5 lamps.

d. Discussion. The results obtained in the experiments are strong evidence that the presence of algae increases the rate of evaporation of water from an algal suspension. The persistence of this difference throughout the range of light energy input rules out any differences due to viscosity, if there were any. The fact is, however, a determination of the viscosity of the algal suspension and of water alone (i.e., plus nutrient salts) showed that their respective viscosities were almost identical. Temperature and relative humidities at each of the light energy inputs to the two were similar. The increase in rate of evaporation brought about by the presence of algae in a suspension ultimately is due to the chlorophyl content and photosynthetic activity of the algal cells. The algae act as black bodies in that they absorb light energy and convert a large fraction of it to heat energy. Thus with declining photosynthetic efficiency, a larger and larger fraction of the absorbed light is converted to heat. A simple explanation for the low rate (in comparison to that from the algal suspension) of evaporation from the carbon black suspension and more rapid increase as light energy was increased is that the viscosity of the carbon black suspension was

about 31 per cent greater than that of either the algal suspension or of water alone.

After appropriate taste tests, the consensus (including non-biased observers) was that the reclaimed water had no objectionable flavors, and in fact lacked the "flat" taste characteristic of conventionally distilled water. The reason for the absence of the flat taste is that the water is well aerated because it condenses as a thin layer on the cooling coil and thus a considerable amount of oxygen may diffuse into it.

The relatively high yield of water, even when no carbon black or algae were present, is an indication of the effectiveness of the gas exchange that takes place in the algatron. In the course of evaporation, water molecules leave the rapidly moving surface as vapor which is swept away by movement of air over the surface. Rapid mixing of the liquid film brings about a high rate of gas exchange for both CO_2 and O_2, thus no bubbling aeration or diffusion aeration is required.

4. MODIFICATION OF THE MICROTERELLA

Because of the very favorable results obtained in our studies, the incorporation of an algatron system into the microterella was indicated, especially since with such an arrangement it would be possible to study the algatron as a functioning part of an integrated life support system. To accomplish this, a number of modifications had to be made in the microterella unit. The modifications were mainly those concerned with the removal of the culture from the bottom of the microterella jar and containing it in an algatron, and the elimination of the mixing pump, since mixing would be accomplished by means of a suitable probe in the algatron.

A diagrammatic sketch of the modified microterella is shown in Figure 3. The algatron used in the microterella consists of a clear plastic drum 10 in. in diameter and 6 in. high capable of holding up to 4 liters of culture. The drum is open at the top and enclosed at the bottom. As the figure shows, the algatron is suspended by a shaft which projects through the central column and which is rotated by means of a belt drive from a motor mounted on the exterior of the microterella

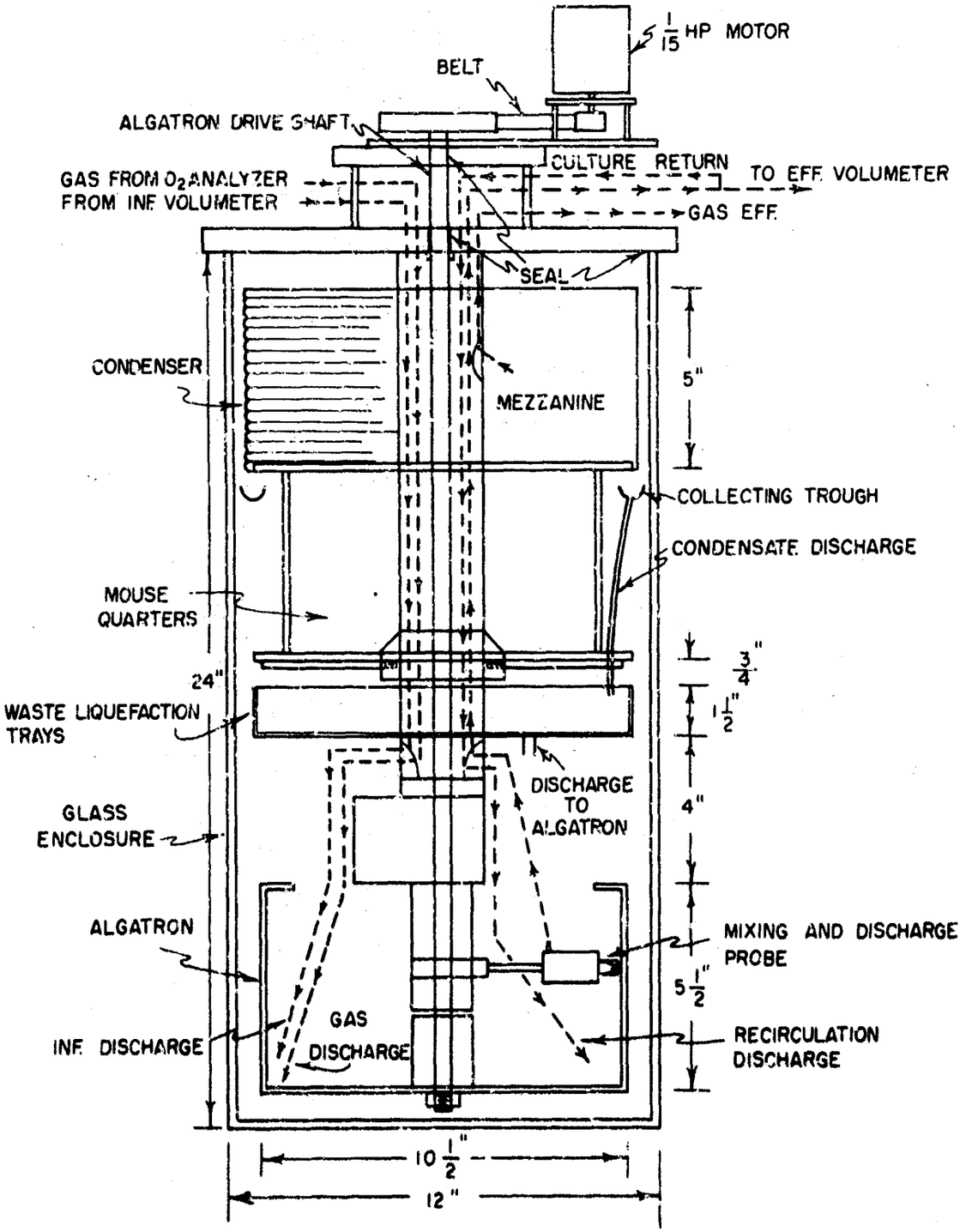


FIGURE 3. ARRANGEMENT OF ALGATRON AND SOLID WASTE LIQUEFACATION TRAYS IN THE MICROTERELLA

housing. An "O-ring" packing seals the shaft at its exit point and prevents gases from entering or leaving the microterella. At first a worm gear drive and motor located directly above the algatron was tried. However, such an arrangement had to be discarded because of the excessive wear and tear encountered due to backlash when the algatron was stopped. The motor and belt drive had to be mounted on the exterior of the microterella because of space limitations within the unit.

A single probe fulfills the triple function of mixing, effluent discharge, and recirculation. Effluent discharge and recirculation are accomplished through the expedient of using a T arrangement to channel to the effluent volumeter a portion of the suspension scooped from the culture by the probe, and returning the remainder to the culture via the recirculation circuit shown in Figure 3. The amount discharged as effluent is regulated by the effluent volumeter. The operation of the latter has been described in a previous report [8]. The kinetic energy of rotation ($V^2/2g$) is converted to potential energy head at the orifice to move the liquid to the effluent volumeter. With the drum rotating at 22 fps, water can be raised approximately 8 ft by this method.

Because of the "close tolerance" of the probe-culture arrangement, any large-sized particles in the revolving culture would be lodged against the probe and thus cause extensive splashing. Because of this danger, it is necessary to prevent mouse droppings from falling into the algatron. This was accomplished by suspending two interconnecting trays beneath the floor of the mouse living quarters. The trays are 1-in. deep (cf. Figures 3 and 4). A set of two trays was used so that the trays could be easily removed without the need for dismantling the central column, as would have been necessary had a single completely circular tray been used. Water that is collected on the condenser is discharged into these trays. Inasmuch as this water is rich in oxygen, some oxidation of mouse waste occurs in the trays. Because of the high surface-to-volume ratio of the liquid in the trays, the trays with their contents serve as miniature oxidation ponds. The trays are provided with overflow structures through which water-bearing dissolved fertility is discharged into the algatron.

Insufficient time has elapsed between the completion of the modifications of the microterella and the writing of this report to

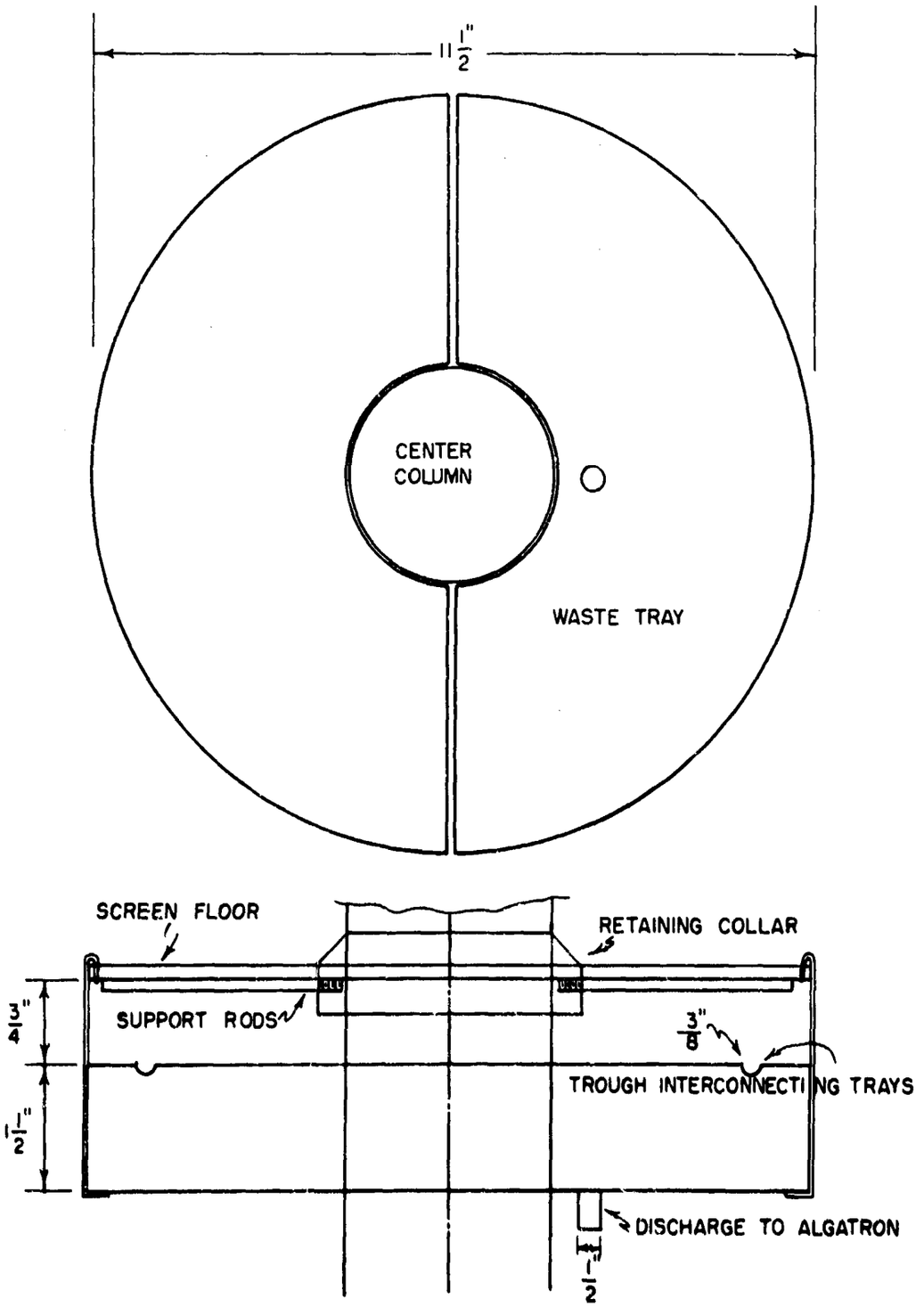


FIGURE 4. DETAILS OF ARRANGEMENT OF WASTE LIQUEFACTION TRAYS IN THE MICROTERELLA

allow for the conduct of any experiments with the unit. However, performance of the unit will be dealt with in detail in the 10th and 11th quarterly reports.

5. DESIGN OF A TWO-MAN MANNED SYSTEM—STATIC EARTH MODULE

5.1 Purpose: To design a system for two men, having the following characteristics:

a. Microbiological regenerative cycles for:
   1) Oxygen generation
   2) Carbon dioxide absorption
   3) Waste disposal
   4) Odor control.

b. Physical regenerative cycles for:
   1) Temperature control
   2) Water recovery
   3) Humidity control.

5.2 Parameters:

a. Load—2 men @ 70 kg
b. Energy source—solar or simulated solar
c. Food—packaged, dehydrated
d. Duration—indefinite (3 months)
e. Nutrients—exhaled CO_2, feces, urine, miscellaneous body secretions, wasted food, plus supplementary nitrogen and phosphorus.

5.3 Methods:

a. Oxygen regeneration—algae growth
b. Carbon dioxide absorption—algae growth
c. Oxygen utilization—men + bacteria
d. Carbon dioxide production—men + bacteria
e. Water regeneration—evaporation + condensation
f. Refrigeration—evaporation + condensation
g. Odor control—liquid trapping + aerobic microbial oxidation.

5.4 Design Elements of System:

a. Men (specifications for food and oxygen requirement)
b. Algatron culture system design
c. Oxidation cells
d. Illumination system
e. Cooling system

Men: 2 @ 70 kg. Daily caloric intake of 2,500 calories/man/day = 5,000 calories. The oxygen requirement is 3.67 calories/gram of O_2. Oxygen required = 5,000/3.67 = 1,360 grams/day. Algae/oxygen ratio = 1.67 grams of O_2/gram of algae. Therefore, the growth requirement = 1,360/1.66 = 820 grams of algae/day.

Algatron Culture System Design: Since experimental algal yield in the algatron is 1.5 grams/liter/day, at detention period 1 day there are 1,500 mg/liter of algae and since 820 grams of algae are to be produced, we will need 820/1.5 = 550 liters of solution. At a 1.5-cm depth and 18-in. diameter for the algatron, we may then compute the cylindrical length of algatron which will have a volume of 550 liters. The diameter of algatron = 18 in. x 2.54 = 45.7 cm; the circumference of the algatron = 45.7 + 42.7/2 = 140 cm; and the volume per centimeter = 140 x 1.5 = 210 cu cm/cm length. Thus 1 liter will require 1,000/210 = 4.78 cm of cylinder length per liter. Total volume = 550 liters; therefore we need 550 x 4.78 cm/liter = 2,630 cm. Available length of 18-in. diameter plastic tubes = 4 ft 0 in. = 122 cm. Therefore, 2,620/122 = 21.8 tubes. (Use 22 tubes.) Assume rotation to produce acceleration equal to 20 x gravity; then $r\omega^2$ = 644 ft/sec^2 whence N, the rotational velocity, = 296 rpm; therefore, use 300 rpm.

Thus we have 22 algatrons 4 ft. high x 18 in. diameter with 1.5-cm depth algal cultures which rotate at 300 rpm. The air-water interface area = 1.78 sq m/unit; the illuminated area = 3.56 sq m/unit.

Oxidation Cell Design: Purpose: to oxidize liquid-carried food and body wastes within the capsule and render them satisfactory for application to the algatrons. The quantity

of water involved in liquid carriage of wastes will be determined by the rate of evaporation which in turn is determined by thermodynamic considerations of heat transfer. In the integrated environmental control-life support concept, heat will be transferred by means of a reflux evaporation condensation system which will essentially make available quantities of water proportional to heat transferred.

On the basis of empirical evaluations made in earlier studies with the microterella, quantities of water which will be available for waste disposal are evaluated at about 10 gallons/man/day. Thus, assuming a 12-hour detention period for two men, the oxidation chamber volume requirement will be 10 gallons. Although 10 gallons may seem to be a large volume, it should be recognized that each of the biological reactors will be one of the key storage points for water.

All solid wastes should be thoroughly ground before entering the oxidation chamber and no solids should leave this chamber. A disintegrator or garbage grinder will be used for this purpose. Aeration in the oxidation chamber will be by means of the algatron principle, the only variation being a nontransparent sidewall. Requirements will be met by using a 1.35 cu ft culture vessel for the oxidation cell. A single 4 ft by 18 in. algatron will be satisfactory for this purpose.

Illumination Energy System: For the static earth model the daily food energy requirement is 5,000 k-cal = 5,000,000 gram calories. Assume photosynthetic efficiency = 5 per cent; then the input available energy requirement will be 100,000,000 g-cal = 10^8 g-cal/day. Assume available solar light energy = 0.7 g-cal/sq cm/min. During continuous exposure of 1,440 min/day we will accumulate 1,000 g-cal/sq cm/day. Therefore it will be necessary to admit light through an aperture of $10^8/10^3 = 10^5$ sq cm = 10 sq m. Inasmuch as the total aperture required is 10 sq m and inasmuch as there are 22 units, the total aperture requirement is 0.45 sq m/unit. Computation will show that this area can be developed by using 5 apertures

12 in. in diameter for each (aperture = 900 sq cm x 5 = 4,500 sq cm = 0.45 sq m).

As a practical matter, it may be more sound from both a structural and an illumination standpoint to use a single large aperture for each of the algatrons. A typical design is shown in Figure 5. As is evident in the figure, the design takes into consideration the structural problem of a large glass plane and the fact that the algatron must be exposed edgeways to the light and must have a bearing in the outer edge of the illumination system. (If it were not for this bearing requirement, a glass dome could be used.)

To determine the size of the aperture, we may assume that the circular aperture extends about 15 cm beyond the edge of the algatron (cf. Figure 5). Thus, $\pi(r_2^2 - r_1^2) = 4,500$ sq cm; $r_1 = 15.25$ cm and $r_2 = 45.7$ cm. Then, $A = \pi(45.7^2 - 15.25^2)$ = 5,800 sq cm. Allowing for interference by the structural arches shown in the figure, the total effective aperture should be about 5,800 sq cm less 200 sq cm = 5,600 sq cm. Although this is approximately 1,100 sq cm more than is required, this will permit some regulation of light, perhaps by means of external louvers.

Heat Balance: Inasmuch as the system is to be entirely closed, a heat balance must be carefully made. Assuming adequate external shielding of the chamber itself, internal heat will originate from the occupants and from the illumination system. Two sources of heat must be dealt with in conjunction with the illumination system. One is infrared light and the other is the heat liberated in the algae cultures due to inefficient use of visible light energy.

The quantity of heat to be dealt with in the infrared shields is about 1.3 cal/sq cm/min = 1.3 x 5,800 = 7,500 g-cal/unit/min. Because of the large amount of heat involved, it is essential to exclude this by using glass which will not transmit infrared light. Since this glass will become extremely hot, it will be necessary to protect it from rapid changes in temperature by inner panels of plastic or tempered,

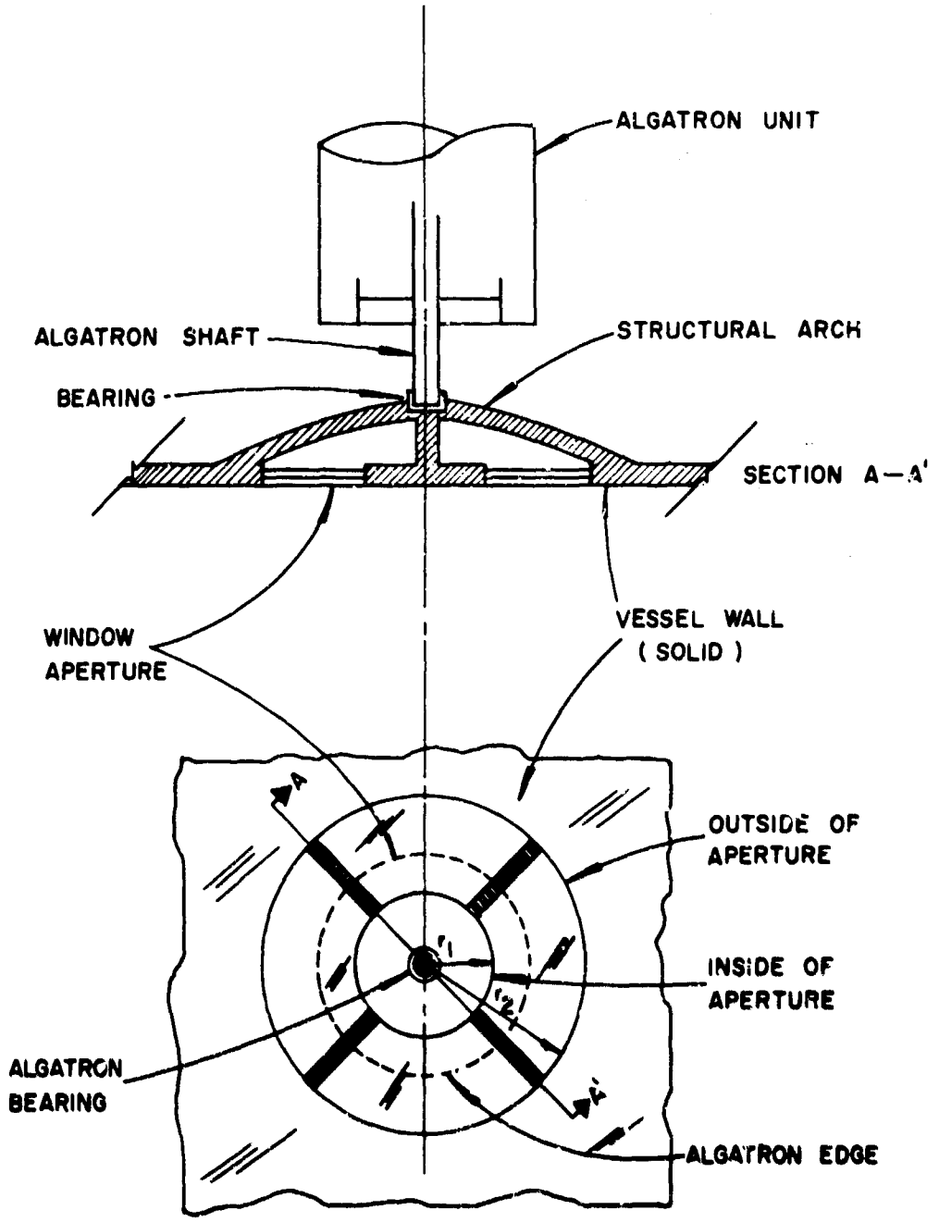


FIGURE 5. APERTURE DESIGN FOR CULTURE ILLUMINATION

heat resistant glass. With regard to the heat produced by the algal cultures, this will be approximately 95,000,000 g-cal/day. Inasmuch as evaporation of 1 gram of water will absorb 590 gram-calories, approximately 160,000 grams of water or 160 liters of water must be evaporated daily.

Studies reported 30 August 1960 showed an evaporative water yield of 4.6 liters/sq m/day from the exposed surfaces of algatrons at 30°C. Inasmuch as the combined exposed surface area of 22 algatrons is 39 sq m, the water yield should be 4.6 x 39 = 178 liters/day. This is well above the 160 liters required for heat transfer and implies that some latitude is available for control purposes.

In order to bring about the effective cooling required, it is necessary to condense the evaporated water from the algatrons (cf. Figure 6). In space there will be available the dark side of the vessel as a radiation sink. However, in the manned system on earth, an external heat sink will be required. This will be provided by means of condensation

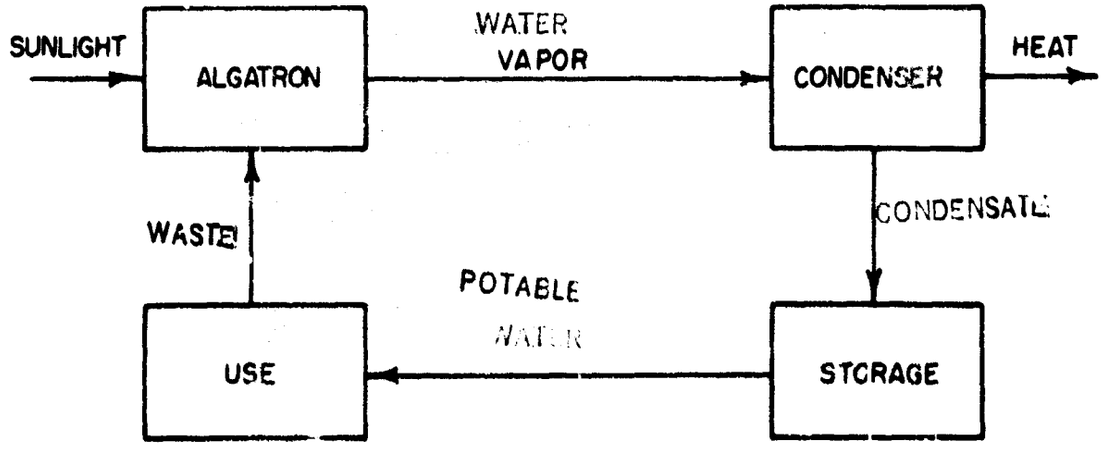
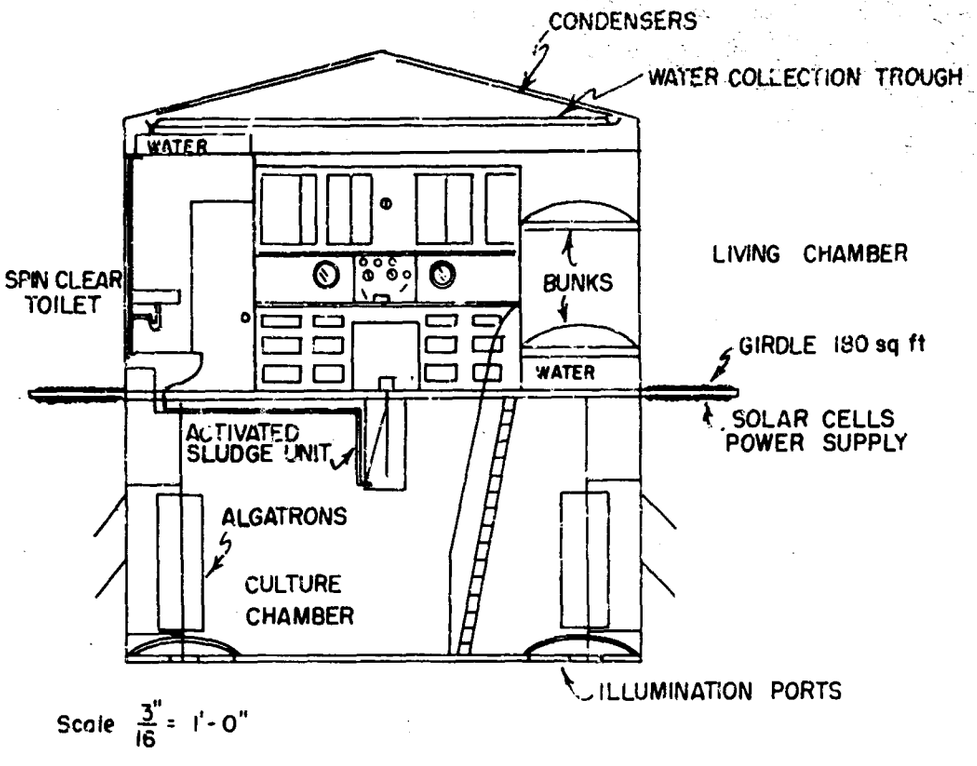


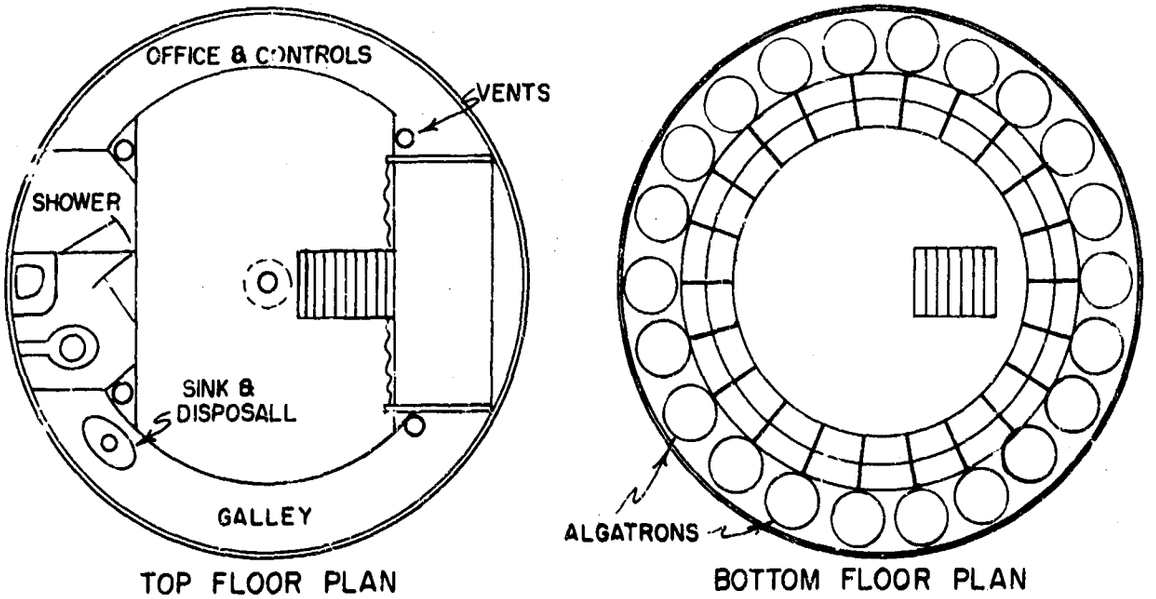
FIGURE 6 . BLOCK DIAGRAM OF REFRIGERATION AND WATER REGENERATION SYSTEM

coils in the ceiling of the capsule. To design these condensing coils, data are available from Figures 21, 22, and 23 of the First Technical Report [1]. For a relative humidity of 60 to 70 per cent and a coil-culture differential of 20°C, condensation rates of 5.4 liters/sq m can be attained. A cooling coil area of 160/5.4 = 30 sq m is thus required. If 3/4 in. aluminum tubing is assumed as the cooling coil material, a specific surface of 6 sq cm/cm is available. The required length of coil then is $30 \times 10^4/6 = 5 \times 10^4$ cm = 5×10^2 m. Assuming a coil diameter of 4.75 m, the length would be 15 m/coil. Required would be $5 \times 10^2/15 = 33$ such coils. A single row of coils would require about 36 in. of depth and therefore would not be feasible. However, if 5 rows of 8 coils turned one above the other were used, the depth of the coil circle could be only 12 in. Another configuration would be a spiral arrangement of the coils. Beginning at the center and spiraling outward with a space of 1/2 in. between each spiral, an area of 30 sq m could be developed with one tier of spiral. This arrangement, however, has the disadvantage of requiring an extensive collecting pan for the condensed water; whereas, the use of 5 rows of 8 coils in tiers would require only a 12 in. wide collecting trough beneath the coils. Thus, 5 rows of 8 coils at a diameter of 14 ft should be used. The cooling surface developed would be 32 sq m.

Integration of the System: An integration of the above design criteria is given in Figure 7 which shows an elevation and two floor plans of the capsule designed in the preceding paragraphs. Excessive details of the design are omitted at this time because precise information, which must be developed in an integrated system, is lacking. The crude essential components of a workable system are, however, integrated in this design. Obviously perfection of the system can only be attained through construction and testing of a complete unit. One factor requiring additional study is the pattern and extent of air movement in the system to provide mass transport of CO_2, O_2, and water vapor. Another factor requiring a great



STATIC EARTH MODULE



TOP FLOOR PLAN

BOTTOM FLOOR PLAN

FIGURE 7. UNIVERSITY OF CALIFORNIA (MECCA) MAN-ALGAL-BACTERIAL ECOLOGICAL CULTURE CHAMBER

deal of study is methods for the use of solar energy to provide electricity to run the various fans and motors in the system.

Manned System, Static Earth Module: In order to demonstrate their confidence in the ultimate feasibility of algal-bacterial life support systems, the University of California has independently undertaken construction of portions of the sealed capsule designed herein and depicted in Figure 7. This capsule will have a "shirtsleeve" environment for two men. This unit, the housing of which is already constructed, is expected to be furnished and instrumented by 1 January 1966. Although it will only contain two algatrons under the current budget, it will make possible short-term calibration and life support studies. When completed, it will embody the integrated life support system herein designed. The major stumbling block to full-scale closed system studies at present is lack of funds to complete the photosynthetic system consisting of 22 algatrons and their associated illumination systems. Should funds become available, it would be possible to have the completely integrated system ready for full-scale, long-term manned studies within about six months. It is hoped that a completely integrated unit would make possible extensive study of effective design of biomechanical systems which could support men in space for indefinite periods of time.

6. SUMMARY AND CONCLUSIONS

The algatron, a growth unit developed during the 1963-64 contract year, which incorporates a mechanically rotated culture as an essential feature, was modified so as to increase light energy flux to the algal culture, to raise the efficiency of the water recovery component, and to improve the mixing action effluent discharge function of the mixing probe.

In experiments on the effect of various environmental factors on yield, maximum production (1.5 g/liter/day) was obtained when the detention period of the biomass was 0.97 day; and that of the liquid

phase, 0.75 day. Inasmuch as yield continued to increase as light energy flux was increased, the limiting factor with respect to yield was light energy flux. (Maximum light intensities at the inner and outer surfaces of the culture that could be attained with the lighting arrangement were 270 and 225 ft-c, respectively.)

No difference was observed in amount of yield under identical combinations of environmental factors when either Oscillatoria sp. or Chlorella sp. constituted the most abundant organism.

As measured by BOD reduction and increase in stability of volatile dissolved solids, from 87 to 91 per cent of the influent unstable dissolved solids were stabilized in a single pass through the algatron system at a liquid detention period as short as 0.25 day. The uniformly high rates of reduction and increase in stability obtained at all of the liquid detention periods tried in the study (0.25 to 1 day) indicate that the minimum length of detention period is less than 0.25 day. Within the range tried, 1.7 to 6.1 days, no difference in stabilization rates could be attributed to biomass detention period.

Within the range of the experimental conditions applied in the study, the principal factor affecting the removal or loss of P, Mg, and Ca was the extent to which the influent concentration of these elements exceeded that needed for growth of the algal cells. The greater the excess, the greater was the loss due to precipitation or to causes other than assimilation. Therefore, the efficient use of these elements requires that they be added to the nutrient medium in amounts approximating those anticipated as being needed for full algal growth. At short biomass detention periods, the initial concentration of ammonia-nitrogen seems to be more decisive in determining the extent of removal than does detention period of biomass or of liquid. Except at the 6.1-day biomass detention period, all of the removal of nitrogen could be accounted for by that in the algal cells, assuming a nitrogen content of 7 to 8 per cent in the cells. Only 52 per cent of the removed nitrogen could be accounted for when the biomass detention period was 6.1 days. The unaccounted for fraction may have been lost as a result of volatilization.

At the highest applied light energy flux, the rate of water recovery was 1.93 ml/min. Rate of water loss, as judged by rate of recovery, was higher from an algal suspension than from water

(containing nutrient salts in a concentration identical with that in the algal suspension) under any of the applied conditions. This difference cannot be attributed to their viscosities, since they were identical in that respect. At a low light energy flux, rate of water loss from a carbon black suspension was less than that from the algal suspension and from water only. However, at the highest applied light energy flux, rate of water loss from the carbon black suspension equalled that from the algal suspension and surpassed that from water alone. The lower rate of loss at a lower light energy flux was due to the greater viscosity of the carbon black suspension--about 31 per cent greater than that of the algal suspension and of water alone.

The microterella was modified by replacing its former algal growth unit component with a new one involving the algatron principle and installing a pair of solid waste liquefaction trays.

A preliminary design of a two-man capsule for long-term life support was made. Essential components of the system are two 70 kg men provided with 1 lb/day of material in the form of dehydrated food, lavatory facilities, a 10-gallon waste liquefier, twenty two 18 in. x 48 in. algatrons and associated illumination systems, a 30 sq m condensing system, and essential fans to provide air transport for CO_2, O_2, and water vapor. Future studies will involve an evaluation of mass transport and materials balances and an evaluation of solar energy to power the system.

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Report on yield of algae, waste treatment, and water recovery with the Algatron and a design for a 2-man life support system.	Hq. AFCRL, OAR (CRF) United States Air Force L.G. Hanscom Field, Bedford, Mass.

13. ABSTRACT

The report describes experiments with an algatron system (i.e., one that involves the use of a mechanically rotated culture) and presents a design of a system to support two men. An average algae yield of 1500 mg/l/day was obtained at inner and outer light intensiteis of 225 and 270 ft-c, respectively, the maximum light intensities obtainable with the available light source. From 87 to 91% of incoming volatile solids were stabilized at detention periods from 0.25 to 1 day. No relation was noted between detention period and removal of P, Mg, Ca, and N. Low temperature distilled water yield was 1.83 ml/sq m/min (ambient relative humidity, 80%). Water losses from an algal culture and from a carbon black suspension were closely similar; and that from both, about 5% greater than from water alone. Design estimates based on the experimental conditions indicate that a maximum of 11 algatrons, each 18 in. in diameter and 4 ft long would be required per man for gas exchange, waste treatment, and water recovery (about 200 liters/day).

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Algae Culture	8	1				
Waste Treatment	8	1				
Water Recovery	8	1				
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